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Surface interpolation within a continental flood basalt province: An example from the Palaeogene Faroe Islands Basalt Group

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ABSTRACT

The Faroe Islands Basalt Group (FIBG) is a continental flood basalt province with four proven lithohorizons that have abundant spot height data. The spline interpolation method was used to construct spatial surfaces for the lithohorizons. The resultant surfaces conform to dip and strike estimates that were previously modelled by hand and confirm the methods reliability. The surfaces should be used as guides only, but can be quickly and easily updated as new information becomes available. The surfaces have been used for a variety of different tasks, for example, obtaining gross thickness estimates, producing isopach maps and constructing geological cross-sections. An additional benefit of the spatial surfaces is the ability to constrain disparate observations in a stratigraphic framework, which will be particularly important for future studies attempting to understand, for example, the temporal and spatial development of continental flood basalt volcanism. The spline interpolation method applied in this study can be equally used for other stratigraphic horizons (e.g. chemohorizon, chronohorizon, biohorizon) and in other continental flood basalt provinces (e.g. Deccan Traps, Columbia River Basalt Group).

1. Introduction

The often monotonous appearance and lack of or inaccessible exposure within continental flood basalt (CFB) provinces can make it difficult to constrain the stratigraphic position of isolated observations. This is important when samples are collected to test, for example, the effects of CFB provinces on palaeo-climate change, e.g. geochronological (palynological or radiometric) and geochemical studies (e.g. Self et al., 2006). The ability to constrain spatially extensive observations in a stratigraphic framework will also considerably improve our understanding of the evolution of CFB provinces and help develop 3D models (e.g. Jerram and Robbe, 2001; Single and Jerram, 2004).

In order to achieve this, a stratigraphically defined surface needs to be extrapolated beyond the extent of observations consisting of widespread spot height data. Traditionally, this would be achieved through the triangulation, also known as the three-point problem, of the spot height data and the resulting structural contours would be interpolated across and extrapolated beyond the study area. This method however, produces straight and angular lines for the structural contours that are geologically improbable and in the majority of available Geographic Information Systems (GIS), e.g. ArcGIS 9.2®, the structural contours produced by triangulation (i.e. Triangulated Irregular Networks (TIN)) cannot be easily extrapolated outside the extent of the dataset.

This study describes an alternative methodology employed in ArcGIS 9.2® to extrapolate spot height data to produce a spatial surface on a regional scale. The exposed remnant of the Palaeogene Faroe Islands Basalt Group (FIBG) on the Faroe Islands, NE Atlantic Ocean is chosen as the test area because it has four proven lithostratigraphic surfaces (lithohorizons) with abundant spot height data (Rasmussen and Noe-Nygaard, 1969, 1970; Passey and Jolley, 2009). Different spatial interpolation methods are evaluated through numerical comparison and by contrasting the modelled results to published surfaces that have been drawn by hand. This evaluation process led to the consistent application of the spline tool, part of the spatial analyst extension and the settings applied are presented. The resulting surfaces have been used for a variety of different tasks and include, for example, extracting surface elevations and estimating stratigraphic thicknesses at disparate locations. As an adjunct, the thickness variations across the islands are discussed based on the construction of cross-sections and isopach maps using the interpolated surfaces.

2. Faroe Islands Basalt Group

The FIBG in the NE Atlantic Ocean has a minimum areal extent of ~120,000 km^2 and an exposed remnant of ~1400 km^2 occurs on

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the Faroe Islands (Passey and Jolley, 2009). Across the archipelago the FIBG has a gross stratigraphic thickness of ∼6.6 km, where the basal ∼3.4 km has only been proven in the Lopra-1/1A borehole (Fig. 1). The FIBG is subdivided into seven lithostratigraphic formations dominated by basalt lava flows and minor volcaniclastic (sedimentary and pyroclastic) lithologies and this study utilises the lithostratigraphy of Passey and Jolley (2009). The archipelago is made up of 18 main islands ranging is size from 0.8–373.5 km^2. The mountainous islands have an average height of 300 m above mean sea level (amsl) and expansive exposures of the geology are limited to near-vertical, inaccessible cliff sections. Inland, profiles through the stratigraphy are primarily restricted to stream sections, although thick (>10 m), tabular sheet lobes (flow lobes that have widths significantly greater than their thicknesses) often form prominent benches that can be traced between streams and around mountainsides.

The base of the FIBG is represented by the ∼1.1 km thick Lopra Formation composed of volcaniclastic lithologies, the majority of which are interpreted as hyaloclastites (Ellis et al., 2002; Waagstein, 2006; Passey and Jolley, 2009). The Lopra Formation is overlain by the ∼3.25 km thick Beinisvørð Formation dominated by laterally extensive, subaerial basalt sheet lobes (Passey and Bell, 2007). The upper surface of the Beinisvørð Formation was eroded down to the second highest sheet lobe and

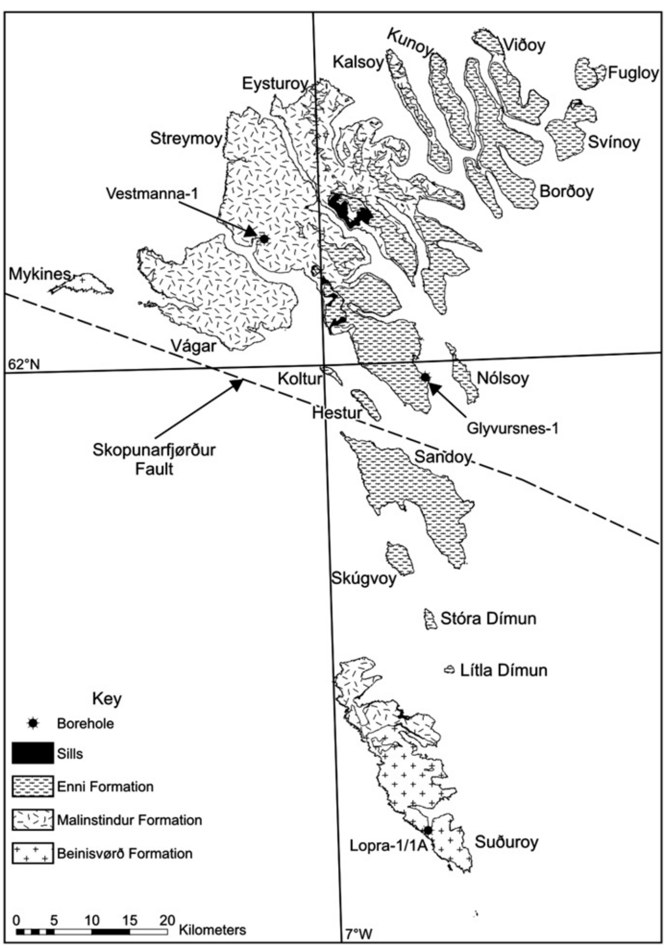

Fig. 1. Simplified geological map of the Faroe Islands showing the three main basalt-dominated Beinisvørð, Malinstindur and Enni formations, the large sills and the supposed Skopunarfjørður fault. The Prestfjall, Hvannhagi and Sneis formations are too small to be shown at this scale. The locations of the three deep scientific boreholes, Lopra-1/1A, Vestmanna-1 and Glyvursnes-1 are indicated on the map. The map is modified after Rasmussen and Noe-Nygaard (1969, 1970), Passey and Bell (2007) and Passey (2009).

marks an unconformity with the overlying <15 m thick Prestfjall Formation (Rasmussen and Noe-Nygaard, 1969, 1970). The unconformity is referred to as the Beinisvørð-Prestfjall Unconformity (BPU) and is exposed on the islands to the south and northwest of the archipelago: Suðuroy, western Vágar and Tindhólmur (Fig. 1; Passey and Jolley, 2009). The Prestfjall Formation is composed of coals, claystones and sandstones deposited in swamp, lacustrine and fluvial environments (Lund, 1989; Ellis et al., 2002; Passey and Jolley, 2009). These units are locally overlain by the Hvannhagi Formation that is exceptionally up to 50 m thick and is composed of airfall tuffs and mass flow deposits (Passey and Jolley, 2009).

Lava flow volcanism resumed with the emplacement of the <1.4 km thick Malinstindur Formation dominated by subaerial compound lava flows tens of metres thick, which are made up of thinner flow lobes up to a few metres thick (Passey and Bell, 2007). Within the Malinstindur Formation there are, however, a number of laterally extensive volcaniclastic units. One such example is the Kvívík Beds that occurs about two-thirds above the base of the Malinstindur Formation and commonly consists of a bedded volcaniclastic sandstone sequence up to 1.5 m thick (Passey and Jolley, 2009). The Kvívík Beds are generally found towards the base of a ∼100 m thick interval dominated by brown weathering, aphyric to olivine-phyric compound basalt lava flows with a distinctive low-TiO_2 geochemistry (Rasmussen and Noe-Nygaard, 1969, 1970; Waagstein, 1988). The Kvívík Beds are exposed across SE Vágar, northern Streymoy and along the NW coastline of Eysturoy (Passey and Jolley, 2009).

The upper surface of the Malinstindur Formation is reddened due to weathering and marks a disconformity surface (Malinstindur-Sneis Unconformity (MSU)) overlain by the laterally extensive Sneis Formation (Passey and Jolley, 2009). The Sneis Formation is up to 30 m thick and is typically composed in northern areas by a sandstone and conglomerate pairing that thins to <2 m thick sandstones on Hestur and Sandoy (Passey, 2009; Passey and Jolley, 2009). The occurrence of the conglomerate-dominated Sneis Formation in the field is strikingly obvious due to the ubiquitous association with brown weathering, aphyric to olivine-phyric tabular invasive basalts which contrasts with the surrounding dominantly pale weathering, plagioclase-phyric compound basalt lava flows (Passey, 2009; Passey and Jolley, 2009). The MSU is exposed across the islands of Sandoy, Hestur, Koltur, Streymoy, Eysturoy, Kalsoy, Kunoy, Borðoy and Viðoy (Fig. 1).

The Sneis Formation is overlain by the >900 m thick Enni Formation composed of both subaerial compound lava flows and sheet lobes of differing petrologies (plagioclase-phyric, aphyric and olivine-phyric) and weathering colours (pale vs. brown; Passey and Jolley, 2009). Approximately, 200–300 m above the base of the Enni Formation the lava flows are punctuated by the laterally extensive volcaniclastic sequence, the Argir Beds (Ellis et al., 2009; Passey, 2009; Passey and Jolley, 2009). The Argir Beds are known to be exposed as far south as Skúgvoy and are also observed on the islands of Sandoy, Hestur, Streymoy, Eysturoy, Borðoy, Kunoy and Viðoy with the inference that they should also crop out on the island of Kalsoy (Fig. 1, Passey, 2009). The Argir Beds are on average 4 m thick but locally obtain thicknesses of ∼13 m (Passey and Jolley, 2009). Even where the Argir Beds are poorly developed the surface can still be recognised because it corresponds to a disconformity surface in the volcanic pile that marks the appearance of brown weathering, olivine-phyric lava flows on the northeastern islands and pale weathering, plagioclase-phyric sheet lobes across Sandoy, Streymoy and Eysturoy (Ellis et al., 2009; Passey and Jolley, 2009). It has been estimated that a few hundred metres have been eroded from the FIBG (Waagstein, 1988).

The FIBG was emplaced during the Palaeocene and Eocene, when the Faroe Islands and East Greenland were <100 km apart prior to the opening of the NE Atlantic Ocean in magnetochron C24R during the early Eocene (Saunders et al., 1997; Larsen et al., 1999; Jolley and Bell, 2002). After the emplacement of the FIBG, assumed thermal contraction of the putative-Iceland plume in the Eocene resulted in magmatism being restricted to the active rift system which resulted in subsidence in the Faroe-Shetland region (Saunders et al., 1997). Andersen (1988) suggests that this subsidence, most likely, resulted in the gentle (<4°), easterly to south-easterly dip of the lava flows on the Faroe Islands.

3. Methodology

3.1. Spot height data

The following lithohorizons, from oldest to youngest, were selected from the FIBG to be interpolated: the Beinisvørð-Prestfjall Unconformity (BPU), the base of the Kvívík Beds, the Malinstindur-Sneis Unconformity (MSU) and the base of the Argir Beds. The first three surfaces correspond approximately to the A-, B- and C-horizons of Rasmussen and Noe-Nygaard (1969, 1970), respectively. The majority of the spot height data (219 points) used for the three oldest surfaces were obtained from Rasmussen and Noe-Nygaard (1969, 1970). Additional spot heights (68 points) for these surfaces and the base of the Argir Beds were obtained through fieldwork (Passey, 2006, 2009; Passey and Jolley, 2009 and this study) and from onshore geotechnical (Borðoyartunnilin 2007-3; Gásadalstunnulin 1989-1; Sandoyartunnulin 2005-2, 2005-3 and 2007-5; Skálafjarðartunnulin 2006-1, 2006-2 and 2006-4 and Viðareiðistunnilin 2007-1) and scientific (Glyvursnes-1 and Vestmanna-1) boreholes (Waagstein and Hald, 1984; Heinesen, 1989; Waagstein and Andersen, 2003; Ólavsdóttir, 2005; Madsen, 2006; Højgaard, 2007a,b, 2008).

Spot height data was collected in the field using a Garmin® eTrex Vista® HCx or a GMAP® 60CSx GPS receiver that have reported horizontal and vertical accuracies of <10 m and ±3 m. The spot heights were entered into ArcGIS 9.2® as x, y, and z points in the ED50 UTM29 map projection (same as the readily available topographic maps). The values were then cross-referenced and validated against 1:20,000 topographic maps, colour aerial photographs and digital elevation models. Through this validation process it is estimated that the spot heights have horizontal and vertical accuracies of 1–2 m.

It should be noted that the FIBG has been intruded by the large Streymoy, Eysturoy and Svínoy-Fugloy sills (Fig. 1), which have uplifted the MSU in the order of a few tens of metres (Rasmussen and Noe-Nygaard, 1969, 1970). The affect of this uplift was not accounted for in this study (i.e. no spot heights were collected from above the sills) and therefore, the interpolated surfaces should be regarded as pre-intrusive surfaces. The locations of the sills are however, delineated on the resultant surfaces.

3.2. Spatial interpolation

The purpose of spatial (surface) interpolation is to estimate values of some property (e.g. precipitation, temperature, topography, etc.) at arbitrary unsampled sites within an area covered by a set of existing discrete observations, distributed uniformly or non-uniformly. A cornerstone in spatial interpolation is the assumption that observations close together are more likely to have similar values than observations spatially far apart (Tobler, 1970), implying that data exhibit a spatial dependency. There are a variety of different interpolators (e.g. kriging, inverse distance weighting (IDW), spline) that can be used to model this spatial dependency.

The authors are aware of only two examples using surface interpolation and 3D model building using discrete observations to construct structural contours in a CFB province. These are the modelling of lava flows in the Huab Basin in the southern part of the Etendeka flood basalt province, Namibia (Jerram and Robbe, 2001) and in Talisker Bay, Isle of Skye, NW Scotland (Single and Jerram, 2004). These examples unfortunately do not cite or explain the method of surface interpolation or accuracy of the modelled surfaces. It is imperative therefore, to examine the different types of surface interpolation and identify the most suitable method for the dataset in this study.

Many of the different interpolation methods (kriging, IDW, spline) have been compared using both theoretical and real datasets of topographic, climatic or geophysical origin (e.g. Enriquez et al., 1983; Weber and Englund, 1992; Mitášová and Hofierka, 1993; Hutchinson and Gessler, 1994; Laslett, 1994; Declercq, 1996; Han and Yu, 1996; Zimmerman et al., 1999; Chaplot et al., 2006; Yue et al., 2007), but general conclusions on which method is best suited are equivocal, but generally the most appropriate method depends on the distribution of data points and the property studied (Childs, 2004).

The dataset used in this study consists of unevenly distributed spot height observations and the chosen interpolation method must therefore, have the ability to handle irregularly spaced data as well as produce a surface that passes as closely as possible through the spot height values and produce a smooth rather than abrupt surface that will more closely resemble previously modelled surfaces by hand. In ArcGIS 9.2® there are several interpolation methods that fulfil these criteria (i.e. kriging, IDW, tension spline and regularised spline).

Before these methods could be tested it was important to consider the effect of faulting on the interpolation surfaces. Rasmussen and Noe-Nygaard (1969, 1970) have shown however, that most normal and strike-slip faulting is generally less than a metre to several metres and consequently, localised faulting is considered to have had only a minor affect on the surfaces. Passey (2009) has suggested however, the presence of the large-scale, ESE-trending Skopunarfjørður fault between the islands of Sandoy and Hestur (Fig. 1). This fault has been estimated to have a vertical discontinuity of 200–300 m, which may be accounted for by lateral movement of between 4.2 and 6.2 km (Passey, 2009). It is therefore necessary to take this fault into consideration in the interpolation of the surfaces. This was achieved by separating the spot height data for each lithohorizon into two areas, north and south of the Skopunarfjørður fault, respectively. This resulted in the BPU and the base of the Argir Beds lithohorizons requiring two interpolation surfaces each. The base of the Kvívík Beds and MSU lithohorizons only have abundant spot height data north of the fault and therefore, each lithohorizon required only one interpolation surface. In summary, the presence of the fault meant the interpolation of six surfaces for the four lithohorizons.

In order to ensure a consistent approach in the interpolation of the lithohorizons a bounding area was required to define the extent of the analysis. This rectangular area corresponds to the eastings 566000 and 644000 (78 km wide) and the northings 6802000 and 6923000 (121 km long). The bounding area covers the entire Faroe Islands, including peripheral skerries, and has a buffer zone of ~1.8–7.0 km between the coastlines of the main islands and the edge of the bounding area. The surfaces were subsequently clipped into smaller geographically defined areas to account for the Skopunarfjørður fault and to confine the interpolated surfaces to the datasets.

The different interpolation methods (kriging, IDW, tension spline and regularised spline) were tested upon the six datasets for the four lithohorizons. The parameter for the output cell size was set to 100 points and as the coordinate system is in metres this equates to a cell size of 100 by 100 m (i.e. 943,800 cells). This cell size was considered suitable for the size of the bounding area and meant that computation time was kept to a minimum. The number of points used in the calculation of each cell was left unmodified utilising the default setting of 12 points, where the value for each cell is calculated based on the 12 nearest observed spot height values.

The conformability of the produced surfaces was evaluated through numerical comparison of the observed and modelled values following the scheme of Willmott (1982). The accuracy of the tested methods (kriging, IDW, tension spline and regularised spline) for the chosen surfaces, using the default settings in ArcGIS 9.2®, is generally good. The maximum Mean Absolute Error (MAE) is 1.4 m for the base of the Argir Beds in the southern area using the kriging method. For the majority of the tested surfaces the kriging method returned the highest MAE values, whereas the other methods usually have MAE values on the centimetre to decimetre scale. It is also clear that the scatter in the accuracy (i.e. smallest values of MAE) of the tested surfaces is not solely dependant on the number of spot heights. In summary, the margins of error are small and based on the numerical comparison alone one could conclude that all the interpolation methods honour the observed data.

It was necessary therefore, to evaluate the modelled surfaces using other geological evidence (e.g. field, seismic, magnetic and gravity data and previous studies). The kriging and IDW surfaces produce bulls-eye anomalies that do not conform to the known geological understanding of the area, whereas the spline methods produce gently dipping surfaces that compare with previous strike and dip estimates and structural surfaces drawn by hand

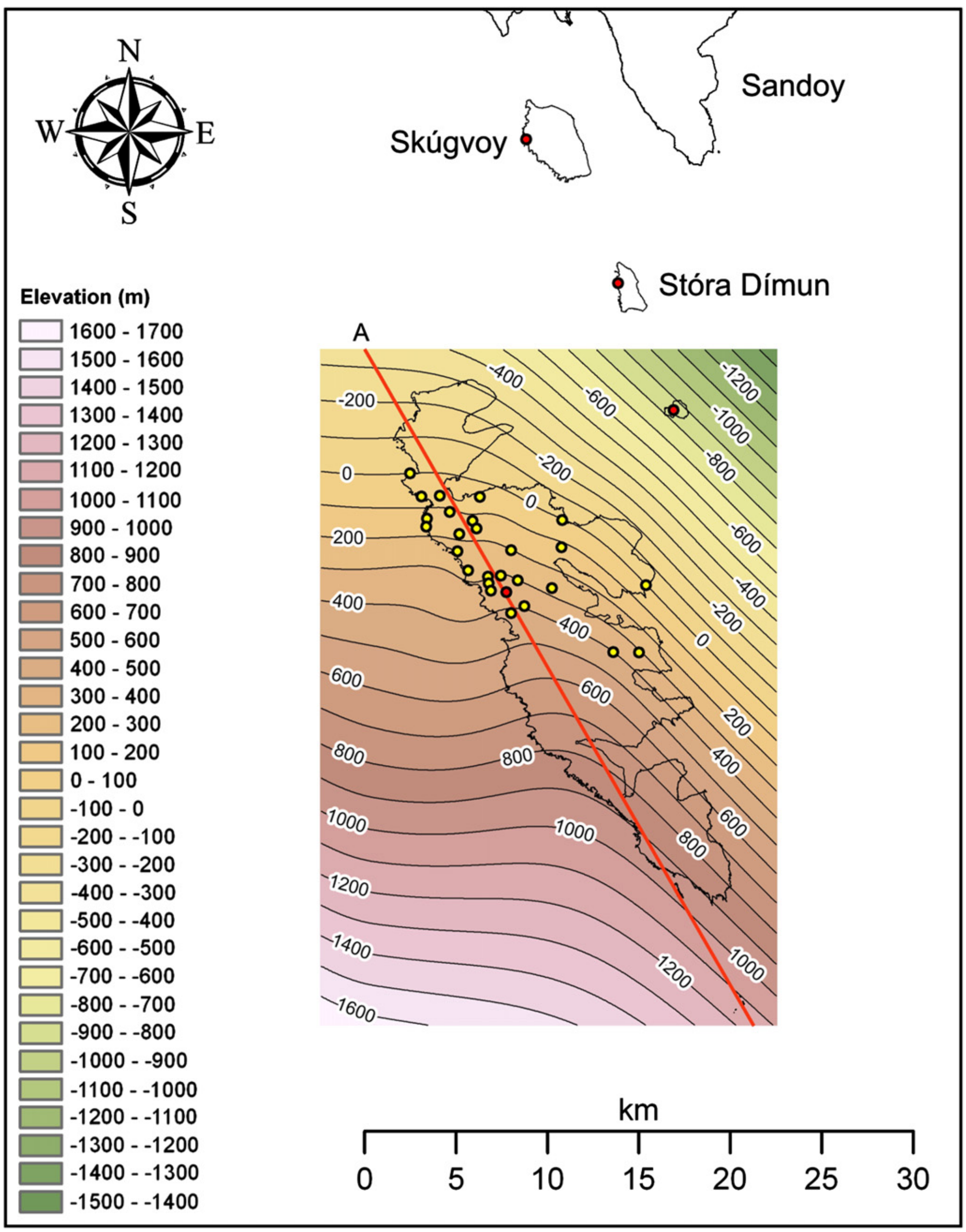

Fig. 2. Interpolated surface map for the Beinisvørð-Prestfjall Unconformity (BPU) covering the southern area. The spot heights used to produce the interpolation are represented by yellow circles. The red circles represent the highest points on the islands shown (Table 3). The route for cross-section A, as depicted in Fig. 7a, is delineated by a thick red line.

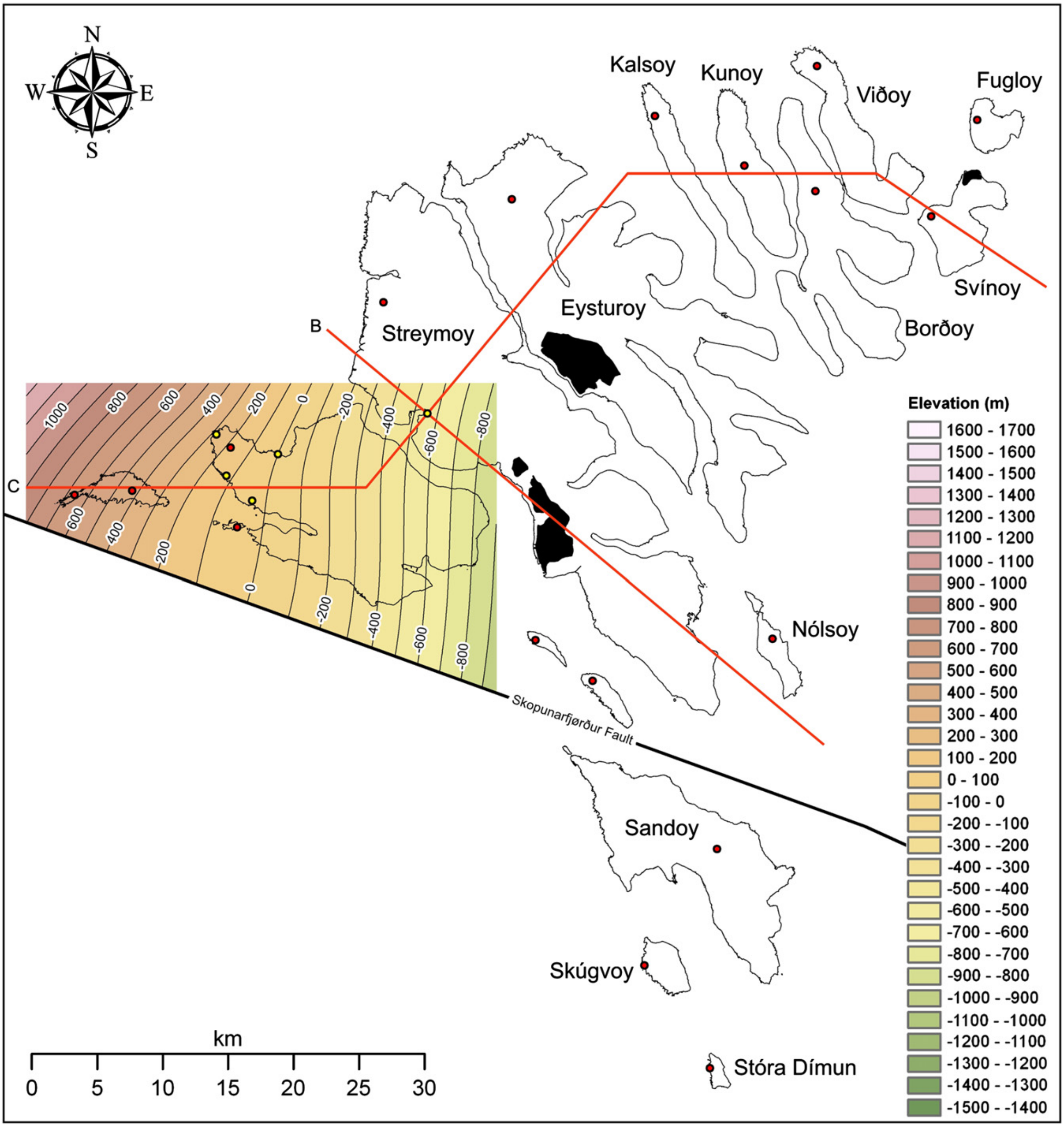

Fig. 3. Interpolated surface map for the Beinisvørð-Prestfjall Unconformity (BPU) covering the northern area. The spot heights used to produce the interpolation are represented by yellow circles. The red circles represent the highest points on the islands shown (Table 3). The areas affected by the three large Streymoy, Eysturoy and Svínoy-Fugloy sills are delineated irregular black shapes. The routes for cross-sections B and C, as depicted in Fig. 7b and c, are delineated by a thick red lines.

(Rasmussen and Noe-Nygaard, 1969, 1970; Waagstein, 1977, 1988; Hald and Waagstein, 1984; Waagstein and Hald, 1984; Passey, 2009).

Spline interpolation is therefore, considered the most appropriate method for constructing structural contours with the datasets in this study. The spline interpolation method was originally developed for interpolating wing deflections and computation of slopes for aeroelastic calculations (Harder and Desmarais, 1972), but has subsequently been developed for geological applications (e.g. Yu, 1987; Mitášová and Mitáš, 1993), including the construction of structural contours (e.g. Han and Yu, 1996).

In simplistic terms, the spline method interpolates the surface from the spot heights using the minimum curvature spline technique, whereby the surface is bent to pass through all the data points whilst minimising the total curvature of the surface (i.e. like bending a sheet of rubber). Although, the spline interpolator is exact at the data points, in areas between observations, the interpolator will have the tendency to overshoot at highs and undershoot at lows depending on the abruptness in the change of the observed value and the smoothing of the spline (cf. Mitášová and Mitáš, 1993). To minimise these effects and reduce the curviness of the spline even further the spline tool allows two formulations of

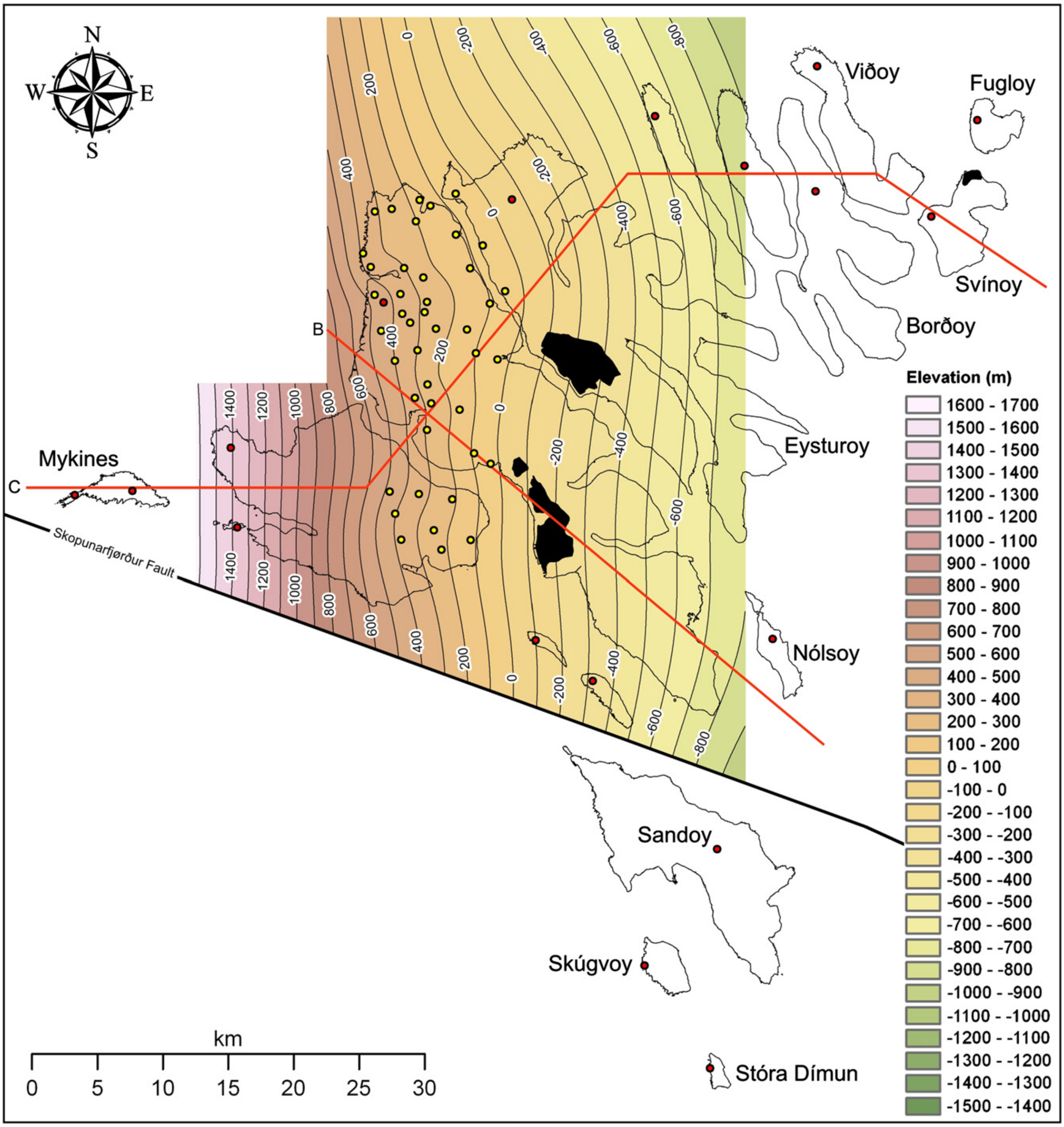

Fig. 4. Interpolated surface map for the base of the Kvívík Beds covering the northern area. The spot heights used to produce the interpolation are represented by yellow circles. The red circles represent the highest points on the islands shown (Table 3). The areas affected by the three large Streymoy, Eysturoy and Svínoy-Fugloy sills are delineated by irregular black shapes. The routes for cross-sections B and C, as depicted in Fig. 7b and c, are delineated by a thick red lines.

spline interpolation to be implemented, regularised or tension spline (Franke, 1982; Mitáš and Mitášová, 1988; Mitášová and Mitáš, 1993). The regularised spline incorporates the first derivative (slope), second derivative (rate of change in slope) and the third derivative (rate of change in the second derivative) into the minimisation calculations, whereas the tension method only utilises the first two derivatives (Childs, 2004). Regularised rather than the tension spline was applied because it creates a smoother, gradually changing surface on a regional scale while minimising the effect of localised topography (e.g. Childs, 2004). The regularised spline also allows the option to define the weight of the third derivative in the curvature minimisation calculations. The higher the weight, the smoother the output surface and values between 0 and 5 are generally suitable, but values of 0, 0.001, 0.01, 0.1 and 0.5 are typically set (Childs, 2004). A number of weights were tested with the dataset, but the median value of 0.01 was considered to produce the most comparable surfaces to those cited in the literature (Rasmussen and Noe-Nygaard, 1969, 1970; Waagstein, 1977, 1988; Hald and Waagstein, 1984; Waagstein and Hald, 1984; Passey, 2009) and was therefore, consistently applied. In addition,

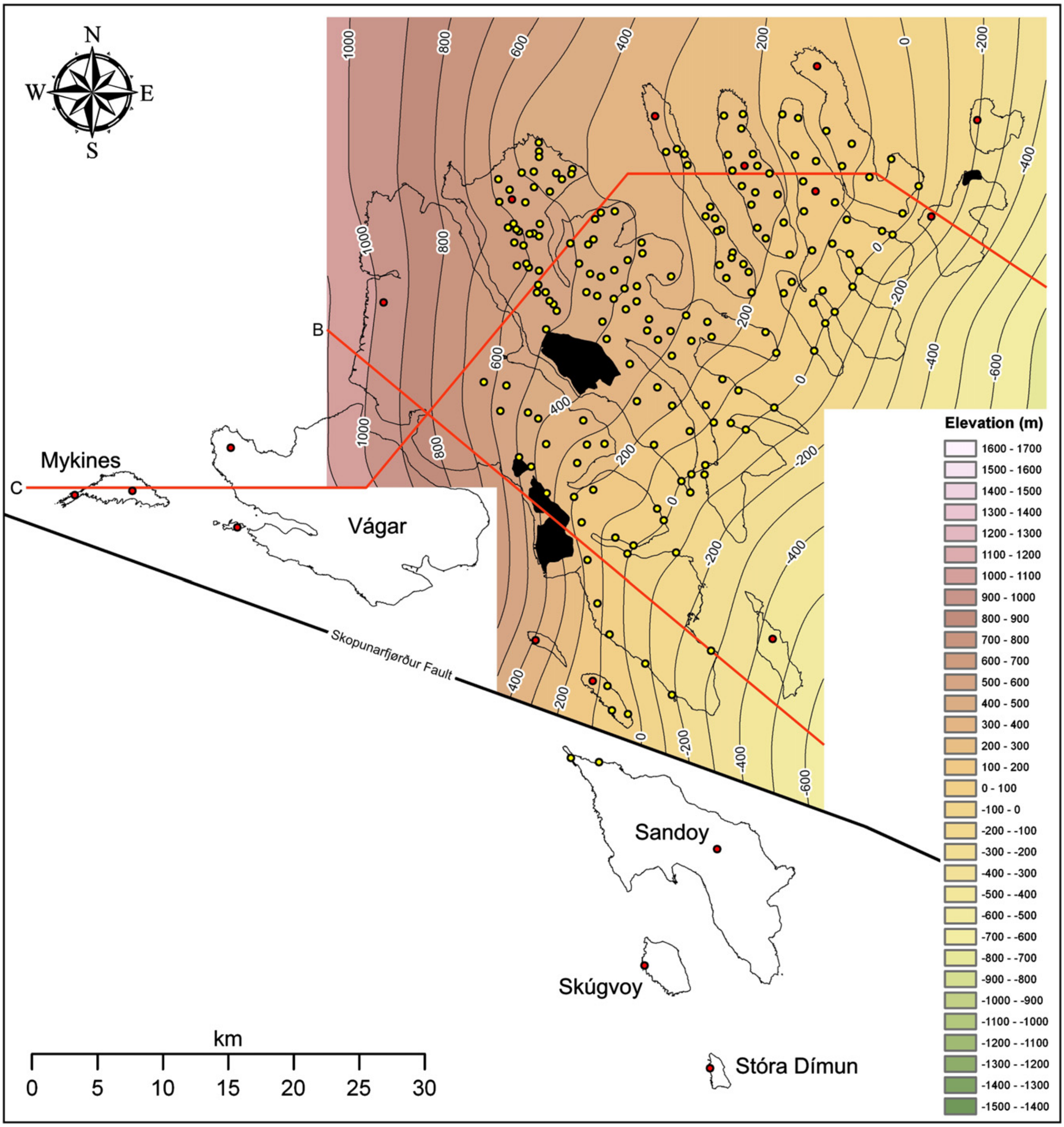

Fig. 5. Interpolated surface map for the Malinstindur-Sneis Unconformity (MSU) covering the northern area. The spot heights used to produce the interpolation are represented by yellow circles. The red circles represent the highest points on the islands shown (Table 3). The areas affected by the three large Streymoy, Eysturoy and Svínoy-Fugloy sills are delineated by irregular black shapes. The routes for cross-sections B and C, as depicted in Fig. 7b and c, are delineated by a thick red lines.

applying the regularised spline with a third derivative weighting of 0.01, generally gave the lowest MAE values when compared to the surfaces produced using the default settings for the examined interpolation methods.

4. Spline surfaces

The interpolated spline surfaces for the BPU, base of the Kvívík Beds, MSU and base of the Argir Beds are presented in Figs. 2–6. Basic information on the interpolated surfaces, including the difference in heights between the measured and modelled values (range: 0–18 cm; average ∼2 cm) can be seen in Table 1. Table 2 provides an overview of the dip and strike data for the interpolated surfaces. The modelled surfaces are scrutinised below to confirm the geological robustness of the interpolation primarily by comparing the predicted strike and dip with those observed in the field and from previous studies (Rasmussen and Noe-Nygaard, 1969, 1970; Waagstein, 1977, 1988; Hald and Waagstein, 1984; Waagstein and Hald, 1984; Passey, 2009). The surfaces are simplistic models that can be easily and quickly updated as new information is added to the dataset, but should be considered as guides only and not the definitive surface for the modelled dataset.

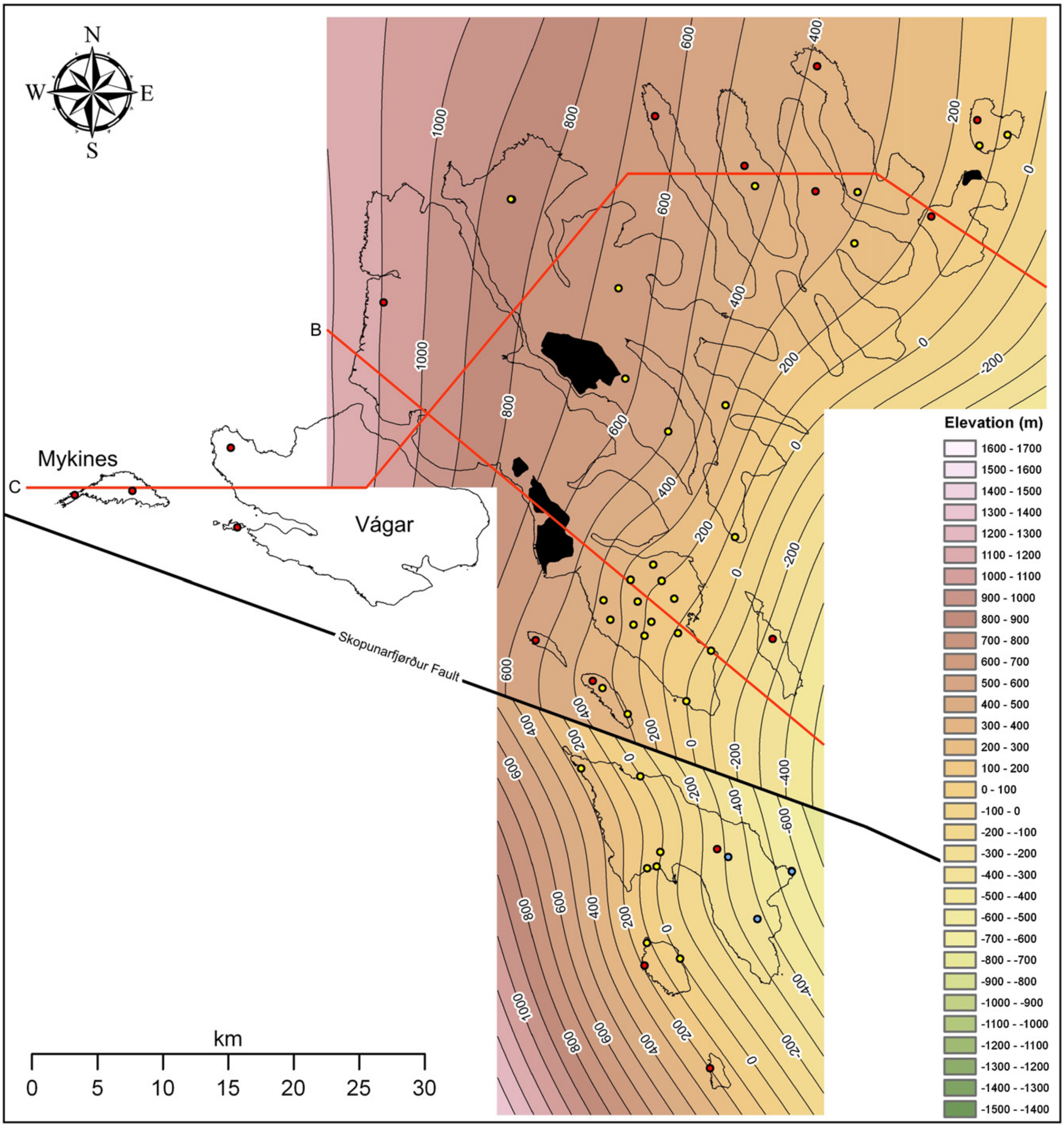

Fig. 6. Interpolated surface map for the base of the Argir Beds covering the southern and northern areas. The spot heights used to produce the interpolation are represented by yellow circles. The red circles represent the highest points on the islands shown (Table 3). The areas affected by the three large Streymoy, Eysturoy and Svínoy-Fugloy sills are delineated irregular black shapes. The three blue circles represent the proposed youngest localities of the FIBG exposed on the Faroe Islands, which are, in order from S-N, Stórafjall (396 m amsl), Skálhøvdi (203 m amsl) and Pætursfjall (447 m amsl). The routes for cross-sections B and C, as depicted in Fig. 7b and c, are delineated by a thick red lines.

4.1. Beinisvørð-Prestfjall unconformity

4.1.1. Southern area

In the southern area the interpolated surface for the BPU has a mean dip of 4.1°, although this varies between 1.1 and 6.4°, and the mean dip direction is to the N–NE (Table 2 and Fig. 2). This is in general accordance with Hald and Waagstein (1984) who recorded average dips of 3.0° to the NE for the lava flows of the underlying Beinisvørð Formation in the vicinity of the Lopra-1/1A borehole on southern Suðuroy. Similarly, the dip measurements obtained from the interpolated surface are supported by Rasmussen and Noe-Nygaard (1969, 1970) who reported dips of between 3.0 and 6.5°. However, dips as high as 16.0° have been reported from the southernmost point of Suðuroy (Waagstein, 1988) and consequently, the interpolated BPU surface may not be as accurate in this area. In addition, the flexures observed in the 300 and 400 m structural contours along the western coastline of Suðuroy (Fig. 2) maybe accounted for by the presence of a normal fault in this area. Rasmussen and Noe-Nygaard (1969, 1970) have shown that this fault has a displacement of up to 11 m but the Prestfjall Formation is

Table 1
Statistics for the six interpolated surfaces.

Surface	Interpolation area	Areal extent (km^2)	Number of spot heights	Density[a]	Difference in heights between measured and modelled values (m)		
					Minimum	Maximum	Mean
Beinisvørð-Prestfjall Unconformity (BPU)	Southern	925	26	2.8	0.0	0.18	0.05
	Northern	618	5	0.8	0.0	0.02	0.00
Base of the Kvívík Beds	Northern	1861	43	2.3	0.0	0.07	0.02
Malinstindur-Sneis Unconformity (MSU)	Northern	2384	180	7.6	0.0	0.13	0.02
Base of the Argir Beds	Southern	694	7	1.0	0.0	0.03	0.01
	Northern	2384	26	1.1	0.0	0.03	0.01
All Surfaces	All	8866	287	3.2	0.0	0.18	0.02

[a] The density column represents the number of spot heights per 100 km^2.

largely unaffected by faulting and consequently, the interpolated BPU surface across the southern area should be considered as generally reliable.

4.1.2. Northern area

The interpolated surface for the BPU in the northern area has a mean dip of 3.2°, although this varies between 0.7 and 4.4°, and the mean dip direction is to the E-SE (Table 2 and Fig. 3). The mean dip and dip direction obtained from the interpolated surface is supported by Rasmussen and Noe-Nygaard (1969, 1970) who reported dips of ~3.0° to the ESE in NW Vágar. A problem exists however with the interpolated BPU surface over Mykineshólmur and Mykines. The interpolated surface predicts that the BPU should be exposed on Mykines, for example, at an elevation of ~430 m amsl, ~130 m below the highest point of Knúker. However, neither the Prestfjall, Hvannhagi or Malinstindur formations have been reported from this island (Fig. 1; Rasmussen and Noe-Nygaard, 1969, 1970), which suggests that the BPU should occur above the maximum height of Mykines and therefore, should not be exposed. This discrepancy between the interpolated BPU surface and mapping in the vicinity of Mykines may be accounted for by increased tilting with dips of between 8 and 20° recorded for the lava flows of the underlying Beinisvørð Formation (Rasmussen and Noe-Nygaard, 1969, 1970). Despite this slight discrepancy the modelled surface across Vágar is very similar to the surface modelled by hand by Rasmussen and Noe-Nygaard (1969, Fig. 133 p. 337).

4.2. Kvívík beds

The interpolated surface for the base of the Kvívík Beds has a mean dip direction to the ENE-E and a mean dip of 3.0°, although this varies between 0.7 and 5.8° (Table 2 and Fig. 4). This is consistent with the dip of ~2.8° for the compound lava flows of the Malinstindur Formation, which dip towards the E in the vicinity of the Vestmanna-1 borehole (Waagstein and Hald, 1984). The dip direction of the Kvívík Beds changes towards the NE in the far north of the interpolation area, which is consistent with the exposures observed in this area where the lava flows of the Malinstindur Formation dip by ~2.2° (Waagstein, 1988). The modelled surface is also very similar to the surface modelled by hand by Rasmussen and Noe-Nygaard (1969, Fig. 133 p. 337). Based on these simple comparisons, it appears that the interpolated surface for the base of the Kvívík Beds is reliable within the confines of the interpolation area.

Table 2
Dip and strike information for the six interpolated surfaces.

Surface	Interpolation area	Dip			Dip direction
		Minimum	Maximum	Mean	
Beinisvørð-Prestfjall Unconformity (BPU)	Southern	1.1°	6.4°	4.1°	N–NE
	Northern	0.7°	4.4°	3.2°	E–SE
Base of the Kvívík Beds	Northern	0.7°	5.8°	3.0°	ENE–E
Malinstindur-Sneis Unconformity (MSU)	Northern	0.01°	5.2°	2.1°	E–SE
Base of the Argir Beds	Southern	0.4°	4.8°	4.0°	NE–E
	Northern	0.4°	4.3°	1.8°	E–SE

4.3. Malinstindur-Sneis unconformity

The interpolated MSU surface has a mean dip of 2.1° but varies from 0.01 to 5.2° and has a mean dip direction to the E-SE (Table 2 and Fig. 5). The dip direction however, changes across the interpolation area (Fig. 5). In the S of the area the MSU dips towards the E, which changes to the ESE/SE approximately along the axial trend of the ESE-trending Kaldbaksfjørður, Streymoy (Fig. 5). In the far N of the islands the dip direction is to the E (Fig. 5). The interpolated surface is very similar to the comparative surface modelled by hand by Rasmussen and Noe-Nygaard (1969, Fig. 133 p. 337), although they suggested the presence of minor faults offsetting some of the structural contours. These faults however, do not appear to affect the relatively conformable structural contours of the MSU modelled in this study (Fig. 5). In general, the dip measurements for the interpolated MSU surface are similar to the sparse data that already exists for the lava flows above and below the MSU, for example, Waagstein (1977) has reported dips of between 1.7 and 2.9° and in the general directions depicted in Fig. 5. There is presently no information to suggest that the interpolated MSU surface should not be regarded as reliable.

4.4. Argir beds

4.4.1. Southern area

In the southern area the interpolated surface for the base of the Argir Beds has a mean dip of 4.0° but ranges between 0.4 and 4.8° and the mean dip direction is to the NE-E (Table 2 and Fig. 6). This is comparable to the measurements made by Rasmussen and Noe-Nygaard (1969, 1970) who observed dips of 3.5° to the NE and ENE on Skúgvoy and Stóra Dímun, respectively. Waagstein (1977) has also reported a dip measurement of 2.5° to the ENE on Sandoy. Passey (2009) also modelled this surface by creating a TIN layer in ArcGIS 9.2® and reported comparable dips of between 2.5° and 4.2° to the ENE and E. There is consequently, no reason to assume that the interpolated surface is unreliable.

Table 3
Extracted elevations from the interpolated surfaces for the highest points on each island and for the three deep scientific boreholes.

Location[a]	Island	Grid reference	Elevation (m)	Elevation of the interpolated surface (m)[b]			
				BPU	Base of the Kvívík Beds	MSU	Base of the Argir Beds
Slættaratindur	Eysturoy	PK 03150 09051	882		−66	**565**	**849**
Villingadalsfjall	Viðoy	PK 26480 19237	841			**146**	**389**
Kúvingafjall	Kunoy	PK 20928 11611	830		−857	**233**	**451**
Kopsenni	Streymoy	NK 93327 01157	789		**439**	978	1095
Nestindar	Kalsoy	PK 14089 15426	788		−622	**312**	**648**
Norðanfyri Lokka	Borðoy	PK 26343 09673	772			**144**	**355**
Árnafjall	Vágar	NJ 81663 90040	722	**178**	1411		
Klubbin	Fugloy	PK 38723 15115	621			−195	**153**
Gluggarnir	Suðuroy	PJ 12181 25699	610	**356**			
Havnartindur	Svínoy	PK 35196 07744	586			−89	**187**
Knúkur	Mykines	NJ 74132 86739	560	**428**[d]			
Tindur	Sandoy	PJ 18831 59369	479				−268
Uppi á Oyggj	Koltur	PJ 04965 75339	477		−102	**388**	534
Múlin	Hestur	PJ 09315 72221	421		−320	**119**	**351**
Rávan	Lítla Dímun	PJ 21341 35666	414	−850			
Høgoyggj	Stóra Dímun	PJ 18294 42597	396				**196**
Knútur	Skúgvoy	PJ 13275 50459	392				**188**
Eggjarklettur	Nólsoy	PJ 23077 75441	372			−439	−240
Tindarnir	Tindhólmur	NJ 82156 83957	262	**48**	1369		
Klettur	Mykineshólmur	NJ 69723 86431	133	664			
Lopra-1/1A	Suðuroy	PJ 18511 14507	11.5 to −3553.5	845			
Vestmanna-1	Streymoy	NJ 96704 92655	2 to −657.7	**−557**[c]	293	814	983
Glyvursnes-1	Streymoy	PJ 18365 74551	16.48 to −683.60		−725	**−282**[c]	**−27**[c]

[a] Locations for the highest points can be seen in Figs. 2–6 and for the boreholes in Fig. 1.
[b] Elevations in bold suggest that the surface should be exposed on the mountain or in the borehole.
[c] These heights were used in producing the interpolated surfaces.
[d] This surface has not been observed on the island.

4.4.2. *Northern area*

The resultant surface for the base of the Argir Beds in the northern area dips between 0.4 and 4.3°, has a mean dip of 1.8° and has a mean dip direction to the E-SE (Table 2 and Fig. 6). As with the southern area Passey (2009) also generated a TIN layer in ArcGIS 9.2® for the base of the Argir Beds across Hestur and southern Streymoy and obtained comparable dips of between 1.9° and 3.7° to the ENE and SE. In addition, the dips and dip directions for the interpolated surface are comparable to those of the interpolated MSU surface (Table 2 and Fig. 5). Therefore, even though the interpolated surface for the base of the Argir Beds is constructed from considerably less spot heights than the MSU surface, the Argir Beds surface should be regarded as reliable in at least the S and SE of the bounding area. The exception is for the north of the bounding area where there is a lack of spot height data (Fig. 6). Despite this, there are indications that the dip direction is changing to a more easterly direction comparable to the directions observed for the MSU in this area (Figs. 5 and 6). The interpolated surface therefore, should be regarded as reliable and can be used as a guide to locate further spot height data in the N and NE of the islands which in the future can be easily incorporated into the dataset to refine the interpolation.

5. Discussion

The interpolated surfaces for the BPU, base of the Kvívík Beds, MSU and the base of the Argir Beds are in overall agreement with the reported dips and strikes from the FIBG and therefore, should be regarded as reliable. The interpolations can consequently be used to extract predicted elevations for these surfaces from disparate locations. Table 3 contains the elevations extracted from the aforementioned surfaces for the highest points from the eighteen main islands and two of the smaller islands as well as for the three deep scientific onshore boreholes (Lopra-1/1A, Vestmanna-1 and Glyvursnes-1). Initially, the interpolated surfaces will quickly allow for the positioning of isolated localities into the stratigraphic framework, which is important for understanding the evolution of the FIBG in terms of, for example, environmental or geochemical development through time.

The interpolated surfaces can also be used to quickly and easily produce cross-sections across the Faroe Islands (Fig. 7), which will help with, for example, the planning of future sub-sea tunnels by correlating surfaces to near-shore seismic sections. Finally, the interpolated surfaces can help elucidate upon the gross emplacement/depositional trends of the lava flows and sediments between the lithohorizons (i.e. the interpolated surfaces). Fig. 8 presents four preliminary isopach maps for intervals between the BPU and the base of the Argir Beds and Table 4 gives basic thickness ranges and means for the analysed intervals.

The gross stratigraphic thickness of the FIBG has been re-evaluated using the interpolated surfaces at key localities, some of which have previously been used for thickness estimates (Table 5). The revised estimate suggests that the remnant of the FIBG has a gross stratigraphic thickness of ∼6.9 km. This is only ∼300 m more than the most recent estimate of ∼6.6 km by Passey and Jolley (2009). The additional thickness has been obtained principally by resolving the exposed thicknesses of the Beinisvørð and Enni formations. In addition, 0.9 ± 0.2 km of missing strata has been estimated using the palaeo-surface predictions of Jørgensen (2006) on Sandoy (Table 5).

Even though it is possible to suggest a gross stratigraphic thickness for the FIBG it should be noted that the cumulative thickness of the different lava formations varies across the islands and indeed the amount of erosion may have also varied (Jørgensen, 2006; Petersen et al., 2006). These thickness variations, as well as systematic trends, are immediately apparent for the isopach maps presented in Fig. 8. Although the thickness trends appear dramatic it must be noted that the changes in vertical thickness occur over distances of many tens of kilometres implying very subtle gradients typically <1°. The persistence and general conformability of the

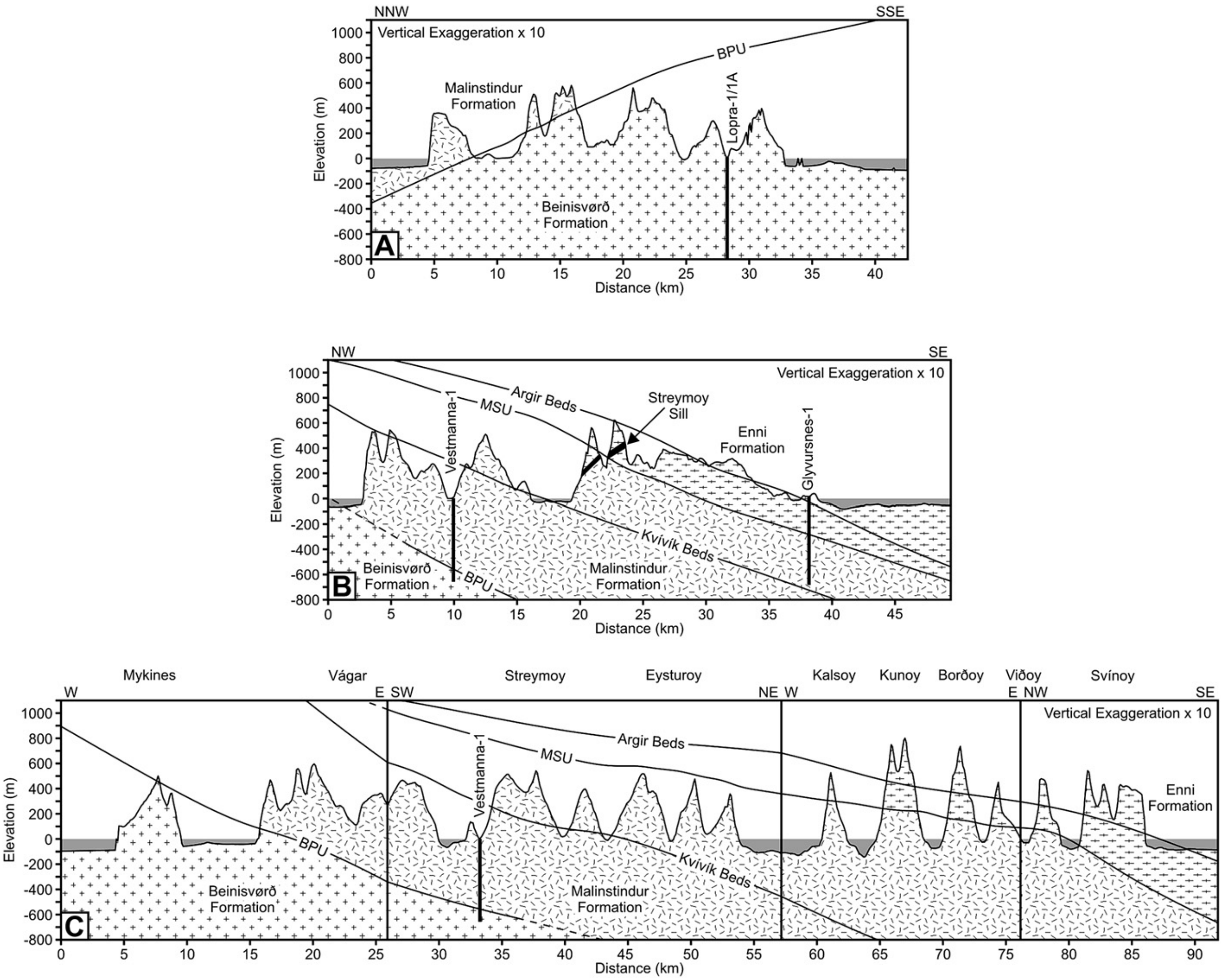

Fig. 7. Three representative cross-sections from across the Faroe Islands that pass through the three deep scientific boreholes, Lopra-1/1A, Vestmanna-1 and Glyvursnes-1 and show the positions of the interpolated surfaces shown in Figs. 2–6. The cross-sections are all drawn to the same scale. (a) Cross-section A traverses Suðuroy from NNW to SSE and the route is shown in Fig. 2. (b) Cross-section B traverses Streymoy from NW to SE and the route is shown in Figs. 3–6. (c) Cross-section C traverses the northern islands from Mykines in the W to Svínoy in the E and the route is shown in Figs. 3–6. Cross-sections B and C intersect at Vestmanna-1.

interpolated surfaces over significant distances (Fig. 7) implies a degree of uniformity and that, regionally planar surfaces were maintained during the construction of this ~1.6 km thick interval of the lava field. This is consistent with the low slopes inferred from morphological features for the compound lava flows that dominate the interval (Passey and Bell, 2007).

The isopach maps for the entire and lower Malinstindur Formation are for small areas where the corresponding interpolation surfaces overlap around Vestmanna and Vágar, respectively (Fig. 8a and b). As a result, no definitive interpretations can be drawn from these maps except that the entire Malinstindur Formation (BPU to MSU) thickens by ~355 m towards the SE (Table 4 and Fig. 8a) and the lower Malinstindur Formation (BPU to the base of the Kvívík Beds) exhibits a fairly uniform thickening trend from ~769 m in the NE to ~1514 m in the SW, a difference of ~745 m (Table 4 and Fig. 8b).

The isopach maps for the upper Malinstindur Formation (base of the Kvívík Beds to the MSU) and the lower Enni Formation (MSU to the base of the Argir Beds) cover much greater areas and can be evaluated with a higher degree of confidence. The two intervals exhibit similar thickening trends from the W/SW to the NE, but are transected by areas of minimal thickness that form crude elongations trending NW–SE (Fig. 8c and d).

When trying to interpret thickness trends in volcanic terrains it is important to remember that unlike sedimentary basins, the emplacement of lava flows and associated pyroclastics can form positive features, such as volcanic edifices (cf. Walker, 1993). Therefore, the natural temptation to interpret the thickest accumulations as depositional centres and the thinnest areas as highs may be reversed in volcanic terrains (cf. Walker, 1995).

The interval between the BPU and the base of the Argir Beds is dominated by compound lava flows that have been interpreted to have been erupted from low shield volcanoes in the immediate vicinity of the Faroe Islands (Noe-Nygaard, 1968; Passey and Bell, 2007). These shield volcanoes, most likely, had limited areal extents and low angle slopes (Noe-Nygaard, 1968; Passey and Bell, 2007). If it is assumed that the thickest accumulations on the isopach maps (e.g. Fig. 8d) represent positive relief (highs) it is

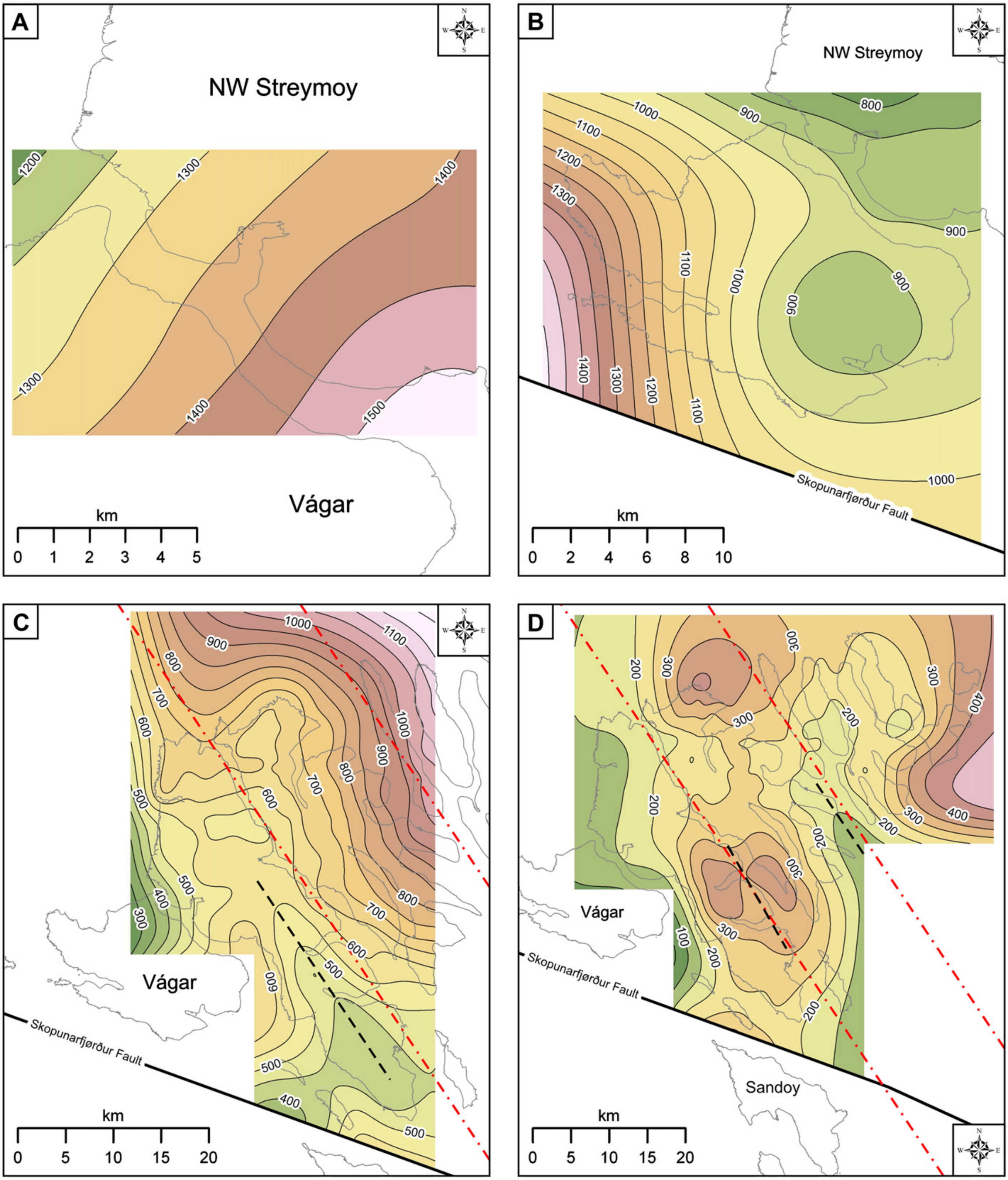

Fig. 8. Isopach maps for selected intervals between the Beinisvørð-Prestfjall Unconformity (BPU) and the base of the Argir Beds. The isopach maps are actually isochore maps, but because the regional dips are so low (~3°), the difference between vertical and true thickness is negligible (e.g. a vertical thickness of 1000 m dipping at 3° equals a true thickness of ~998.6 m, a difference of only ~1.4 m). (a) Isopach map for the entire Malinstindur Formation (Beinisvørð-Prestfjall Unconformity to Malinstindur-Sneis Unconformity). (b) Isopach map for the lower Malinstindur Formation (Beinisvørð-Prestfjall Unconformity to the base of the Kvívík Beds). (c) Isopach map for the upper Malinstindur Formation (base of the Kvívík Beds to the Malinstindur-Sneis Unconformity). (d) Isopach map for the lower Enni Formation (Malinstindur-Sneis Unconformity to the base of the Argir Beds). In parts (c) and (d) the NW–SE trending elongations of minimal thickness are indicated by black dashed lines and the inferred positions of the NW–SE trending Brynhild (left) and Westray (right) lineaments of Ellis et al. (2009) are shown by red dotted and dashed lines. See text for discussion.

Table 4
Thickness information for selected intervals between the BPU and the base of the Argir Beds.

Thickness interval	Thickness (m)		
	Minimum	Maximum	Mean
Lower Enni Formation (Base of the Argir Beds – MSU)	44	491	250[a]
Upper Malinstindur Formation (MSU – Base of the Kvívík Beds)	261	1218	671
Lower Malinstindur Formation (Base of the Kvívík Beds – BPU)	769	1514	1018
Malinstindur Formation (MSU – BPU)	1175	1530	1371

[a] The mean thickness value of ~250 m is comparable to the mean value of ~252 m obtained by Passey (2009) across southern Streymoy and Hestur.

conceivable to interpret them as low shield volcanoes with low angle slopes of <1° (cf. Noe-Nygaard, 1968; Greeley, 1977; Walker, 1993, 1995).

The areas of thickest accumulations are however, commonly overlain by laterally extensive volcaniclastic sedimentary units without any significant litho- and/or biofacies variation, which Ellis et al. (2009) argued, is unlikely if they were deposited on the top, flanks and surrounds of a shield volcano. It is reasonable therefore, to suggest that the intervening lava flows are differentially infilling a subtle palaeo-topography.

If this scenario is correct, then the NW-SE trending elongations of minimal thickness would represent topographic highs (Fig. 8c and d). It is surely more than coincidental that these highs parallel the dominant fjord direction of the islands (Fig. 8c and d) and Ellis et al. (2009) have also suggested that the fjords bound NE to SW thickening of relatively thin (50–200 m thick) lava flow packages. They attributed this thickness distribution and the positions of the fjords to the palaeo-surface manifestation of deep seated NW–SE trending lineaments. This is supported by the symmetry observed in the zeolite zones across the fjords, which Jørgensen (2006) had previously suggested was due to the upwelling of heated palaeo-fluids along NW-SE trending lineaments. Deep seated NW–SE lineaments, commonly referred to as transfer zones, have also been observed on potential field data to the SE of the islands in the Faroe-Shetland Basin and have commonly been named (e.g. Rumph et al., 1993). The Westray lineament, for example, correlates extremely well with the NW-SE trending high that occurs along the fjord between Eysturoy and Borðoy (Fig. 8d).

Lamers and Carmichael (1999), amongst others, have demonstrated that the NW-SE trending lineaments have influenced depositional patterns in the Faroe-Shetland Basin. If therefore, the emplacement and deposition of the lava flows and sediments on the Faroe Islands have been controlled by these deep seated lineaments, then it seems clear that the influence exerted by each lineament varied spatially and temporally during the development of the FIBG. How the lineaments may have controlled the observed emplacement and depositional patterns or what they may represent (strike-slip faults, normal faults, dyke swarms, etc.) is beyond the scope of this study (cf. Ellis et al., 2009; Moy and Imber, 2009). Further investigations are required to constrain the processes involved, but differential subsidence, invoked by Ellis et al. (2009), maybe involved.

6. Conclusions

Four standard interpolation methods (kriging, IDW, tension spline and regularised spline) were tested using default settings in ArcGIS 9.2® on spot height data from the Faroe Islands Basalt Group (FIBG). The interpolation surfaces were numerically evaluated and compared to previous strike and dip estimates and structural surfaces drawn by hand. The surfaces produced using the spline methods (tension and regularised) gave the best results and of the two, regularised spline created a smoother, gradually changing surface on a regional scale while minimising the effects of localised topography. The regularised spline was adapted to incorporate a third derivative weighting of 0.01 that was consistently applied to the four lithohorizons (Beinisvørð-Prestfjall Unconformity (BPU), the base of the Kvívík Beds, the Malinstindur-Sneis Unconformity (MSU) and base of the Argir Beds) analysed from the FIBG.

The four lithohorizons cover a gross stratigraphic thickness of ~1.6 km dominated by thinly bedded compound lava flows of the Malinstindur and lower Enni formations. The surfaces have allowed for a re-evaluation of the gross stratigraphic thickness of the FIBG of <7.75 km in the vicinity of the Faroe Islands, although locally most

Table 5
Revised thickness estimates for the formations of the Faroe Islands Basalt Group.

	Interval	Thickness (m)[a]	Location	Remarks
Sneis and Enni formations	Exposed section of the Enni Formation above the base of the Argir Beds	770	Stórafjall, Sandoy	Exposed maximum thickness
	MSU to the base of the Argir Beds	250	Northern Area	Mean value for this interval (Table 4), which includes the Sneis Formation that has a maximum thickness of ~30 m (Passey and Jolley, 2009)
Malinstindur Formation		1370	Vestmanna-1, Streymoy	Base includes 2.8 m of volcaniclastics belonging to the Prestfjall and Hvannhagi formations (Waagstein and Hald, 1984)
Hvannhagi Formation		50	Suðuroy	Maximum thickness (Rasmussen and Noe-Nygaard, 1969; 1970)
Prestfjall Formation		15	Suðuroy	Maximum thickness (Rasmussen and Noe-Nygaard, 1969; 1970)
Beinisvørð Formation		3325	Lopra-1/1A, Suðuroy	900–1000 m exposed on Suðuroy
Lopra Formation		1075	Lopra-1/1A, Suðuroy	Passey and Jolley (2009)
Total Thickness:		**6855**		This should be regarded as a gross estimate as the thickness varies across the islands
Missing Strata		900 ± 200	Pætursfjall, Sandoy	Utilising the palaeo-surface estimates of Jørgensen (2006)
Gross Total:		**7755 ± 200**		This should be regarded as a gross estimate as the thickness varies across the islands (e.g. 4-5 km thick at Lopra-1/1A, Suðuroy)

[a] Thicknesses rounded to the nearest 5 m.

likely did not exceed 4–5 km. Isopach analysis between the interpolated surfaces recognise the presence of NW-SE trending elongations of minimal thickness that maybe the surface manifestation of the inferred deep seated Brynhild and Westray lineaments.

Future studies in the Faroe Islands are needed to constrain the stratigraphic position of some of the outer islands, for example, Mykines that requires a sub-BPU lithohorizon to be identified. Indeed, the recognition of further stratigraphic surfaces throughout the FIBG will help to elucidate upon the influence exerted by the inferred deep seated lineaments on the emplacement and deposition of the lava flows and sediments of the volcanic pile.

This study has demonstrated the usefulness and applicability of spline interpolation of lithohorizons within a CFB province. The interpolated surfaces can now be used to estimate the stratigraphic position of isolated observations which will help with future geochronological and environmental studies investigating the temporal and spatial development of the FIBG. The application of spline interpolation can be undertaken in other CFB provinces where disparate localities need to be incorporated into a stratigraphic framework. The surfaces investigated can equally be a lithohorizon, chemohorizon, chronohorizon, biohorizon or even a magnetostratigraphic polarity-reversal horizon (cf. Jay, 2005). The settings applied in this study are not definitive and should be evaluated and adapted on a case-by-case basis incorporating both numerical and geological information.

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